High-Fidelity Simulations of Turbulent Flow In Nuclear Reactors

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We performed high-resolution simulations of the turbulent flow that occurs in the core of a pressurized water nuclear reactor. Our goal is to understand the flow-induced vibration problem that results in wear and failure of the fuel rods, forcing full-plant shutdowns and costing utilities millions of dollars every year. The simulations are building a database that will also be used to develop engineering models for future operational use. Analysis of the flow statistics enables a better understanding of how and why the efficiency of cooling is reduced over time and how failure of the fuel rods can be delayed.

Despite the recent Fukushima accident in Japan, worldwide production of electricity using nuclear reactors is increasing with more than 60 reactors under construction in 14 countries. In the US, 80% of the failures in pressurized nuclear reactors, where thousands of hot irradiated fuel rods are cooled by fast-flowing water, are caused by grid-to-rod fretting (GTRF) – a flow-induced vibration problem that leads to wear and failure of the rods. Contact points between the spring and the fuel rod cladding (Fig. 1) cause wear, leading to fuel leakage. If more than a few rods fail in an assembly, plants must be shut down and maintenance costs increase. Typical reactor fuel cycles range from 18 to 24 months, and increasing the life span of reactor fuel significantly improves the economic viability of nuclear power generation.

Fig. 1. Fuel rod assembly.

To understand the root causes of GTRF-induced fuel leaks, we investigate the turbulent coolant flow in the core of nuclear reactors. Our ultimate goal is to accurately predict why, how, and when wear occurs and how it can be prevented or, at least, delayed. Together with industry and university partners, we are developing a computational tool to support the decision-making process in the life-extension of current power plants and to enable the design of safer and more productive next-generation plants.

To date, it has not been possible to fully characterize the reactor-scale GTRF problem involving the thermal-hydraulics of turbulent multi-phase boiling flow coupled to the dynamics of thousands of vibrating fuel rods. As a first step, we report on large-eddy simulations of single-phase flow using two simplified rod bundle configurations (3×3 and 5×5), as shown in Figs. 2 and 3. The simulations explicitly resolve the large-scale motion of the turbulent flow field using first principles and rely on a neutrally dissipative monotonicity-preserving numerical technique to represent the unresolved scales. A small section of a single fuel rod and a spacer grid are shown in Fig. 2 (top), depicting one of the surface meshes used for the computations. The spacer grid supports the rods and its mixing vanes stir the flow in order to enhance the heat transfer between the rod and the coolant. This 3×3 geometry was extracted from a 17×17 fuel-rod assembly found in a typical reactor. There is a large degree of symmetry in the fuel assembly, which makes this geometrical simplification a reasonable approximation. The coolant flow generally moves from upper right to lower left in Fig. 2 (top).

The computational tool that we use, Hydra-TH [1], is being developed by our team at LANL and has the capability to compute high Reynolds number flows in very complex geometries. The code has been exercised with up to 10,000 compute cores to date using the LANL Institutional Computing resources. It yields a detailed time-accurate description of the fluid dynamics of the GTRF problem. As an example, isosurfaces of the helicity are plotted in Figs. 2 (bottom) and 4 at a single time instant for the 3×3 and 5×5 rod-bundle geometries, respectively. Larger helicity corresponds to a more violent turbulent flow and more efficient heat transfer. Although the vortex structures enhance the efficiency of the cooling, they also result in pressure fluctuations on the surface of the fuel rods, thus causing vibrations. The vibrations cause the fuel-rod supports to wear into the protective cladding on the rod surface, which, given enough time, may expose the internal nuclear fuel and result in a fuel leak. Experimental data, provided by Texas A&M University, have been used to validate the statistics of the simulated flow field for the 5×5 rod-bundle. For more details on the fluid dynamics simulations see Christon et al. [2] and Bakosi et al. [3].

We extract the forces acting on the rods in several downstream segments as time-histories, spectra, and integrated statistics from the fluid dynamics simulation. These data are then used to drive a structural dynamics code, VITRAN (VIbration TRansient Analysis–Nonlinear), developed by industry partners, to compute wear. VITRAN uses a modal dynamics approach and incorporates models for grid-to-rod gaps, fuel-rod cladding creep-down, spring relaxation, and grid growth. Understanding

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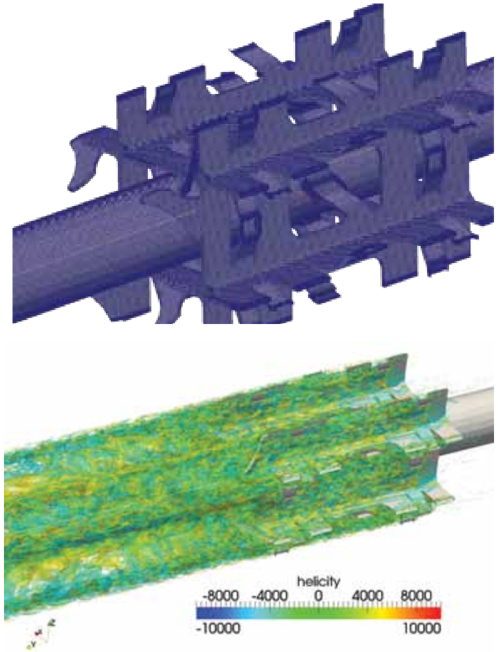

Fig. 2. (top) Surface mesh of small section of a single fuel-rod grid spacer with mixing vanes for the 3×3 rod bundle geometry. Approximate volume-cell count: 47 million. (bottom) Isosurface snapshots of the helicity for 3×3 rod bundle problem, approximate cell count: 47 million.

the detailed interactions of the fluid and structure is critical to mitigating the issues surrounding the GTRF problem.

The high-resolution fluid dynamics simulation data are also the basis for understanding the resolution requirements for future simulations and for developing lower-fidelity statistical turbulence models. These engineering models, specifically developed for the GTRF problem, can then be used operationally in an industrial setting to analyze and assess future rod-bundle designs, such as new spacer geometries, ultimately resulting in safer and higher-energy-throughput next-generation plants.

Future work on GTRF will focus on coupling the structural response of the fuel rods at different dynamic levels of approximation (e.g., one-way, two-way), along with coupling different wear models developed by collaborators in the Consortium for Advanced Simulation of Light Water Reactors (CASL) project, which also includes research staff from the MST and T divisions at LANL. The largest mesh we have run to date for the 3×3 and 5×5 problems have approximately 47 and 96 million computational cells, respectively. In order to adequately resolve the turbulent flow features and the heat transfer along the turbulent boundary layers, we believe that meshes of 100 million to 1 billion elements may be required, depending on plant operating conditions. To incorporate the effects of boiling, multiphase flow models are also being developed and implemented in the Hydra software toolkit.

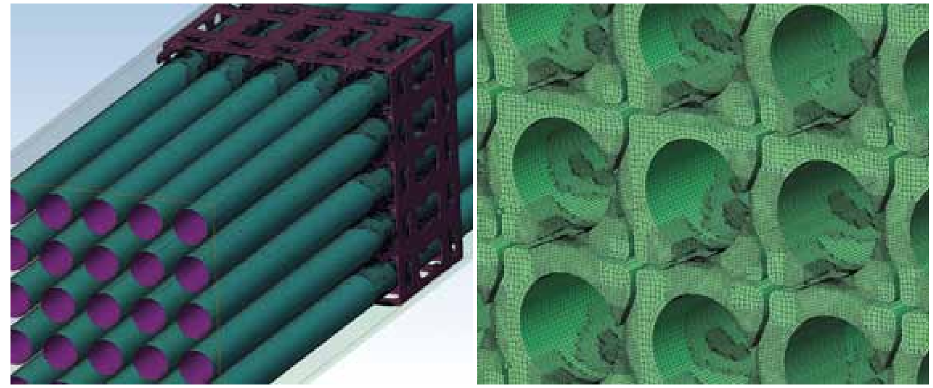

Fig. 3. (left) Surface mesh of spacer grid and fuel rods for the 5×5 rod bundle geometry. Approximate volume-cell count: 14 million. (right) Volume mesh around spacer grid and rods near the trailing edge of the mixing vanes.

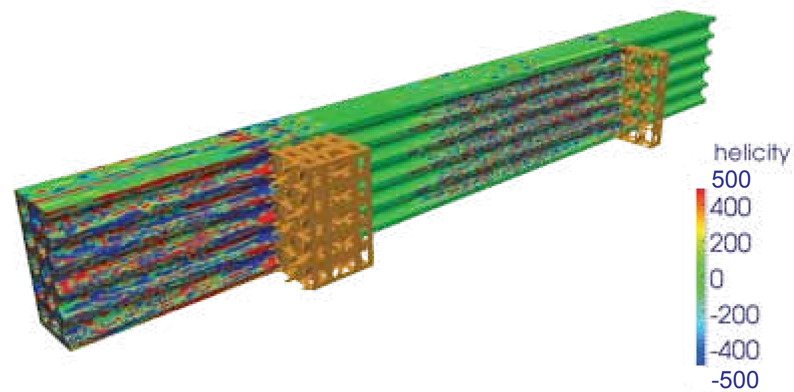

Fig. 4. Snapshots of helicity for the 5×5 rod bundle problem using an approximate cell count of 96 million.

[1] Christon, M.A., “Hydra-TH Theory Manual,” LA-UR 11-05387 (2011).

[2] Christon, M.A. et al., “Initial Assessment of Hydra-TH Code on GTRF Problems,” LA-UR 11-07034 (2011).

[3] Bakosi, J. et al., “GTRF Calculations Using Hydra-TH,” LA-UR 12-24526 (2012).